Characterization of Seismic Source Using Short-Period Seismic Waves

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ABSTRACT

A new algorithm is proposed for the reduction of the complexity of observed seismic waves in the 1-100 sec period band. The algorithm transforms the waveform for an event into a simplified form and is referred to as the Earth simplifying transformation (EST). The event is referred to as the primary event, for which properties of the source are to be determined. The EST algorithm uses data and synthetics for another event nearby, which is referred to as the secondary event. The synthetics are computed for a given Earth model using *a priori* source parameters for the secondary event. Data for the algorithm are regional or teleseismic seismograms, including surface waves and/or body waves. In this algorithm, data for the primary event are deconvolved with the residual waveform which is obtained from the deconvolution of data and synthetics for the secondary event. The residual waveform contains the effects of Earth's structure on seismic waves which are not predicted for the Earth model. The simplified waveform obtained from the algorithm is referred to as the EST seismogram. The EST seismogram represents the waveform which is expected for the seismic waves from the primary event for the Earth model. The source properties for the primary event can be determined from EST seismograms instead of original data, which contain not only the information on the source but also the effects of Earth's structure unpredictable for the model.

Several tests were made using data from earthquakes located in southern California recorded at Global Seismographic Network (GSN) stations, with the distance between the primary and secondary events being less than 100 km. These tests indicate that EST seismograms provide superior resolution power in the source characterization than original seismograms. The major limitation of the procedure is that *a priori* information on the source of the secondary event is required. This procedure can be applied to characterize an explosion source if source parameters for an event nearby are well known, with the secondary event being either an explosion or an earthquake. The application of this procedure may be useful for improving the regional monitoring and discrimination capability under a potential CTBT as well as basic seismological knowledge on source properties of explosions and earthquakes, including magnitude, location, mechanism, and source time functions.

Key words: source parameters, surface waves, nuclear test detection

OBJECTIVE

The objective of this study is to develop and apply new methods for the characterization of the source of explosions and earthquakes using short-period seismic waves, with improved resolution power on source properties, including magnitude, location, mechanism, and source time functions. The accurate characterization of the source with these parameters will improve the regional monitoring and discrimination capability under a potential CTBT as well as basic seismological knowledge on source processes involved in explosions and earthquakes.

RESEARCH ACCOMPLISHED

Our progress in the past year includes mainly two developments: (1) including Earth's aspherical corrections in the computation of synthetic seismograms and in the source determination using recently developed three-dimensional earth models; (2) developing a new procedure for the suppression of noise and unmodeled effects of Earth's structure on observed waveforms.

Although development (1) is of importance to this study, it is not much different from some techniques used elsewhere and thus is not discussed in this report. We will focus on (2), which involves a new data processing algorithm. This algorithm is referred to as the Earth simplifying transformation (EST), which allows us to reduce the complexity or to simplify observed waveforms but still retain the information relevant to the source determination.

Since seismic waves recorded at regional and teleseismic distances from the source are dominated by short-period surface waves in the 1-100 sec period band, it is desirable to use the short-period surface waves for the determination of source properties. However, this is hampered by the complexity of the waves due to the effects of Earth's lateral and radial heterogeneities.

Earth simplifying transformation. A procedure, which transforms a seismic signal into the simpliest form relative to a given earth model. The difference between the simplified waveform and the original signal corresponds to the effects of earth's structure which are not predicted for the earth model; and the signal in the simplified waveform corresponds to the effects that are predictable for the earth model and information on the properties of the source. This procedure enhances signal-to-noise ratio and thus improves the resolution power of short-period surface waves in the source characterization.

Method. According to Gilbert and Dziewonski [1975] the spectrum of a component of ground motion excited by a point source at angular frequency ω for a given earth model may be given by

$$u_k(\mathbf{x}, \omega) = \sum_{i=1}^{6} \psi_{ki}(\mathbf{x}, \mathbf{x}_s, \omega)\, f_i(\omega). \tag{1}$$

where u_k is the k-th record in a set of seismograms, with the receiver at position $\mathbf{x}$ and the source at $\mathbf{x}_s$; ψ_{ki} are excitation kernels and f_i represent six independent components of the moment-rate tensor. For another event located at $\mathbf{x}_s'$ with moment-rate tensor f_i', the spectrum may be given by

$$u_k'(x, \omega) = \sum_{i=1}^{6} \psi_{ki}(x, x_s', \omega)\, f_i'(\omega). \tag{2}$$

Taking into account of our imperfect knowledge of the earth structure and noise generated from other sources, the spectra of observed ground motion for these events may be expressed as

$$U_k(x, \omega) = u_k(x, \omega)\, \alpha_k(x, \omega) + \varepsilon(x, \omega). \tag{3a}$$

$$U_k'(x, \omega) = u_k'(x, \omega)\, \alpha_k'(x, \omega) + \varepsilon'(x, \omega). \tag{3b}$$

where α and α' represent effects of the deviation of the earth's structure from the earth model. In the following analysis the noise terms (ε and ε') are ignored and the event at x_s is referred to as the primary event and the event at x_s' as the secondary event.

In the conventional algorithms the moment-rate tensor of the primary event, f_i, is determined from data for the event, U_k, by solving the following equation

$$U_k(x, \omega) = \sum_{i=1}^{6} \psi_{ki}(x, x_s, \omega)\, f_i(\omega), \tag{4}$$

which is correct to the zeroth-order in terms of α, since implicit in the algorithms is the assumption

$$\alpha_k(x, \omega) = 1. \tag{5}$$

The question that we shall address in this study is as follows. Given a set of seismograms from two events, U_k and U_k', which are located at a close distance along with the synthetics for the secondary event, u_k', predicted for a given earth model, is it possible to determine the moment-rate tensor of the primary event, f_i? For this purpose we define the following transformation

$$u_P^S(x, \omega) = u_k'(x, \omega)\, U_k(x, \omega) \,/\, U_k'(x, \omega). \tag{6}$$

which is referred to as the earth simplifying transformation (EST) in the following analysis.

In general, α and α' in (3) are slowly varying functions of the source location and the moment-rate tensor, with the principle term of their Taylor expansion being independent of the source location and moment-rate tensor and the first and higher order terms much smaller than the principle term. Therefore we assume

$$\alpha_k(x, \omega) = \alpha_k'(x, \omega). \tag{7}$$

Then the right hand side of (6) becomes $u_k(x, \omega)$, thus the spectrum of the EST seismogram may be expressed as

$$u_P^S(x, \omega) = \sum_{i=1}^{6} \psi_{ki}(x, x_s, \omega)\, f_i(\omega). \tag{8}$$

which is correct to the first-order in terms of α and will be used to determine the moment-rate tensor (f_i). For the simplicity of our analysis we adopt a frequently used assumption: f_i are considered to be independent of frequency except for a correction for an assumed duration of the source and are regarded as the moment tensor.

Tests. Several tests were made using data from earthquakes located in southern California recorded at Global Seismographic Network (GSN) stations. Figure 1 shows the location of the primary event (event I: the January 17, 1994 Northridge mainshock, M_s 6.8) and secondary events (event II: an aftershock of the 1994 Northridge earthquake sequence, M_s 6.0; and event III: the June 28, 1991 Sierra Madre earthquake, M_s 5.2) along with source mechanisms for these events obtained previously by various investigators. For the primary event, three solutions of the source mechanism that are shown in Figure 1 are examined using EST seismograms.

Figure 2 shows the waveforms of ground motion recorded at station WMQ and synthetics, bandpass filtered between 7 and 30 mHz. There is considerable discrepancy between the observed waveforms (solid lines under the labels Z_I, R_I, and T_I) and the synthetics (dotted lines under the labels Z_I^{III}, R_I^{III}, and T_I^{II}) for the primary event. In clear contrast, the fit of the synthetics to the EST waveforms (solid lines under the labels Z_I^{III}, R_I^{III}, and T_I^{II}) is excellent.

Figure 3 shows the transverse components of the EST seismograms along with synthetics for the primary event computed for the three source mechanisms that are shown in Figure 1 for several stations in the azimuths between 3° and 12°. For each station, synthetics for different source mechanisms show larger differences in amplitudes. The amplitudes of the synthetics for the mechanism from the regional waveform inversions (B in Figure 3) are in the best agreement with the amplitudes of EST seismograms in comparison with other two mechanisms (A and C in Figure 3).

Figure 4 shows the vertical components of the EST seismograms along with synthetics computed for these source mechanisms for stations at various azimuths. The data shown here represent only a small portion of the whole data set; however, they are more sensitive to the source mechanisms discussed here and have higher signal-to-noise ratio than data for other stations. Analysis of these EST seismograms yields the same conclusion as our analysis of the transverse components: in general, the amplitudes of the synthetics for the mechanism from the regional waveform inversions are in the best agreement with the amplitudes of EST seismograms in comparison with other two mechanisms.

CONCLUSIONS AND RECOMMENDATIONS:

The EST seismograms provide superior resolution power in the source characterization than original seismograms. This method works better for stations at close distances from the source. It is desirable to apply this procedure to data from several underground nuclear explosions in Lop Nor, China, to characterize the source properties of the May 21, 1992 explosion. Another application is to examine the possibility to use earthquakes nearby as the secondary events to identify small explosions. The application may start with the examination of the seismicity near several nuclear test sites in the Central Asia, with both the earthquake and explosion being recorded at regional and/or teleseismic distances.

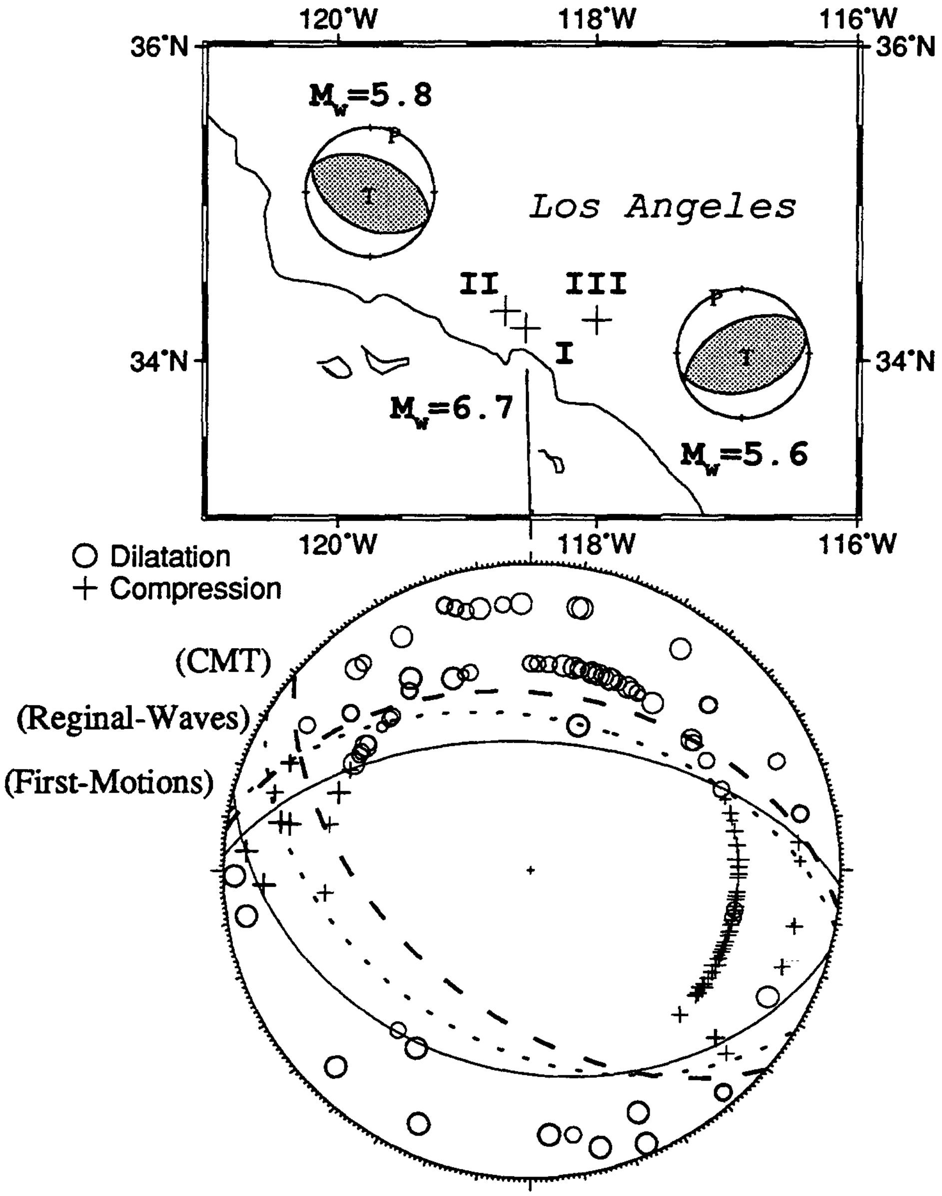

Fig. 1. Location (plusses) and mechanisms of the 1994 Northridge (I: mainshock, II: aftershock) and 1991 Sierra Madre (III) earthquakes. The mechanism for event II is shown for the solution from the regional wave inversions and for event III for the solution from P-wave first motions. Fist motion data are plotted with the uncertainty given by the size of each symbol.

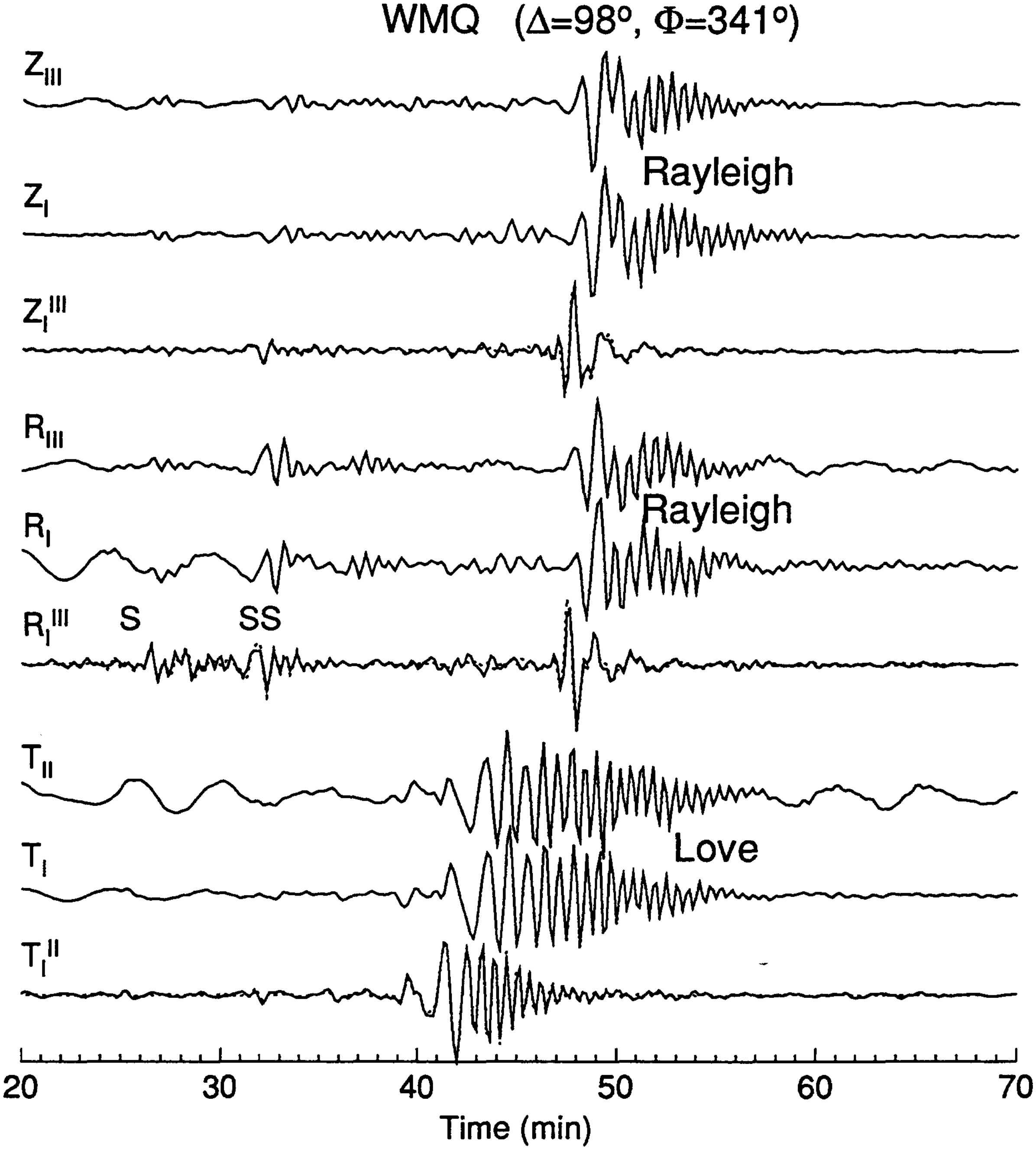

Fig. 2. Data and synthetics for station WMQ (Urumqi, China). Symbols Z, R, and T with subscripts I, II, and III indicate vertical (Z), radial (R), and transverse (T) components of ground displacements, respectively, from various events (subscripts I, II, and III identify the events). Symbols Z_I^{III} and R_I^{III} indicate the EST seismograms obtained using event III as the secondary event, with the synthetics for the event computed using the focal mechanism obtained from P-wave first motions. Symbol T_I^{II} indicates the EST seismograms obtained using event II as the secondary event, with the synthetics for the event computed using the focal mechanism from regional waveform inversions. Dotted lines indicate synthetics for the primary event computed using the focal mechanism from P-wave first motions. Amplitude is arbitraryly set to show waveform coherence. Time is measured from the origin time of the corresponding event.

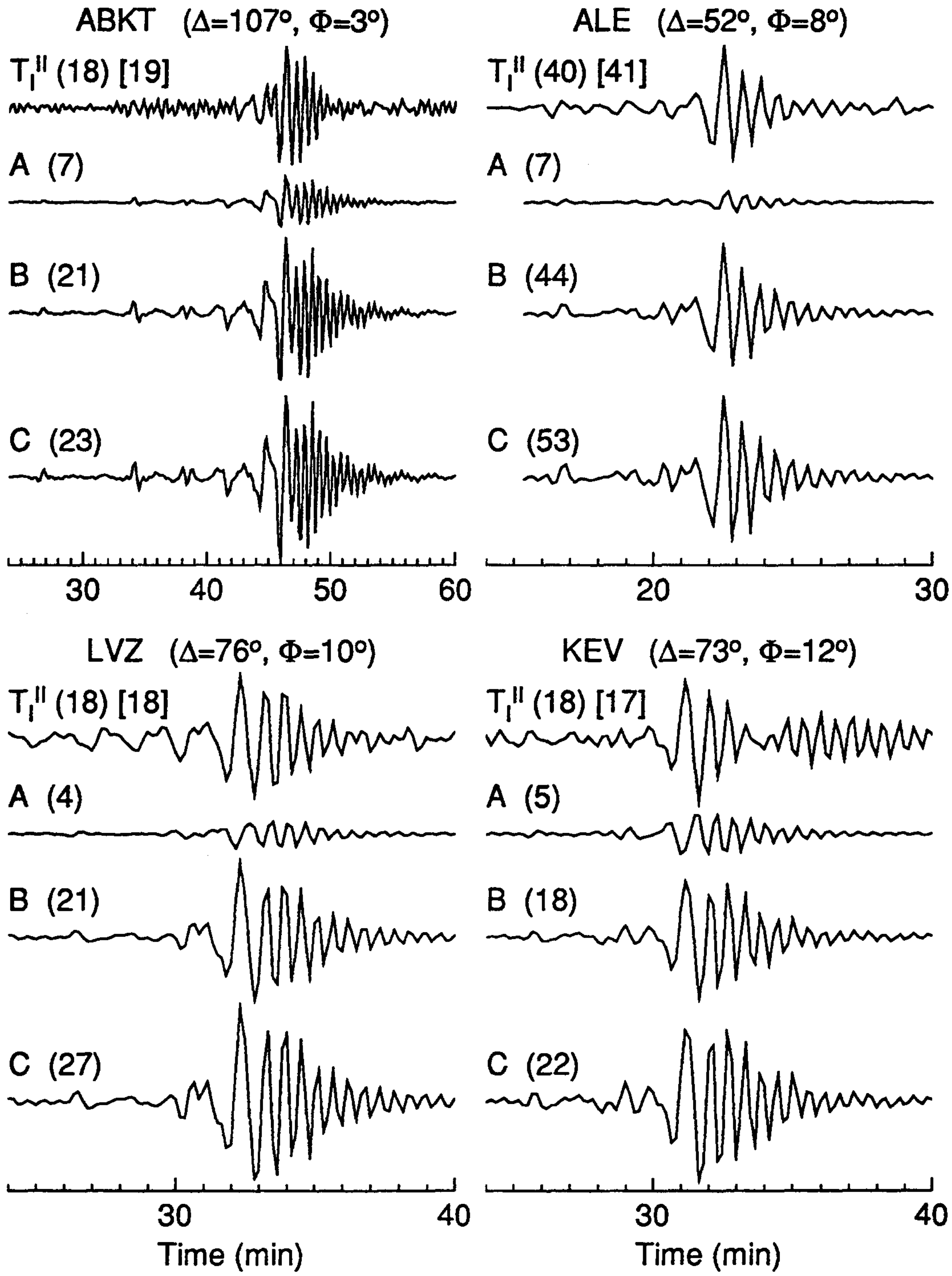

Fig. 3. Transverse components of EST seismograms (T_I^{II}) at various stations obtained with the synthetics for event II computed using the focal mechanism from the regional wave inversions, with amplitudes being given in parentheses in units of microns (amplitudes of T_I^{II} with the synthetics computed for event II using the focal mechanism from P-wave first motions are shown in brackets). Symbols A, B, and C indicate synthetics computed for the primary event using a seismic moment of 1.2×10^{19}Nm and various focal mechanisms: first-motion solution (A), regional-wave solution (B), and CMT solution (C).

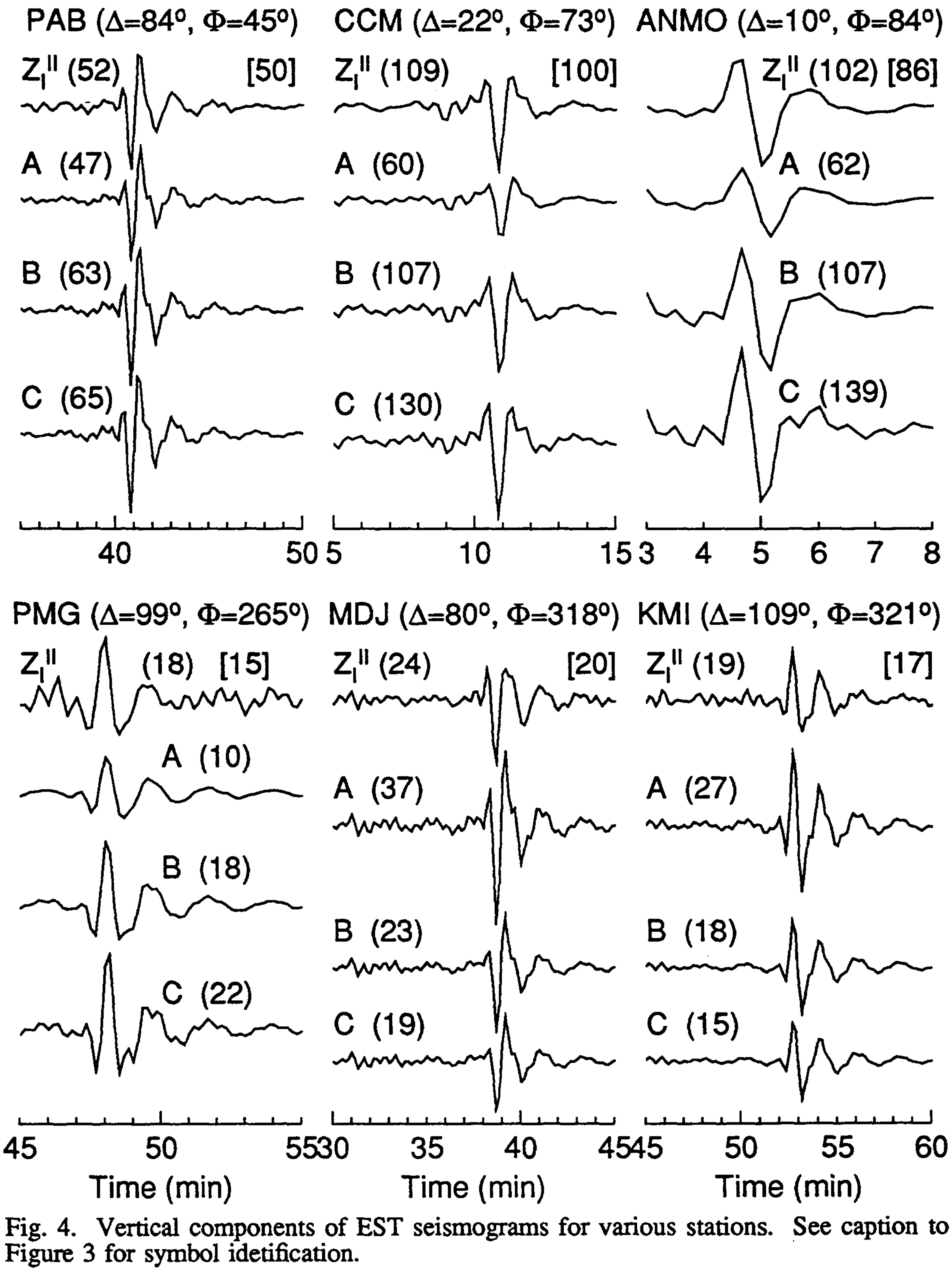

Fig. 4. Vertical components of EST seismograms for various stations. See caption to Figure 3 for symbol idetification.